Evolution of radiation induced micro-damage in the materials used in particle accelerators design

Błażej Skoczeń, Aneta Ustrzycka

Cracow University of Technology, Poland

The present work is focused on constitutive modeling of evolution of radiation induced damage in ductile materials used in particle accelerators design, and subjected to periodic stress states in the inelastic range. During irradiation, energetic particles penetrating a solid displace the lattice atoms from their original positions. Exposure to a flux of particles leads inevitably to creation of clusters of defects in the material, provided that the energy of incident particles is large enough. Collisions of particles of enhanced energy with lattice atoms ejects them from their initial position and transfers the energy to the next collisions with the neighboring atoms. These atomic interactions lead to creation of cascade of atoms moving inside lattice and to production of radiation induced defects in the lattice. Thus, as a result of cascade process, pairs of interstitial atoms and vacancies (the so-called Frenkel pairs) as well as their clusters are created. The evolution of radiation induced damage is combined with the evolution of classical micro-damage of mechanical origin (micro-cracks and micro-voids) within the common framework of Continuum Damage Mechanics (CDM). An additive formulation with respect to damage parameters or tensors has been used. A multi-scale constitutive model comprising the evolution of radiation induced damage under mechanical loads has been formulated. Two well known kinetic laws of damage evolution were taken into account: the Rice and Tracey model and the Gurson model. Both of them address the evolution of porosity in the form of spherical or ellipsoidal voids in a different way. The Rice & Tracey model predicts the evolution of radius of spherical void as a function of triaxiality and the accumulated plastic strain. It is expressed in the form of differential equation and has therefore implicit character. In order to compute the damage parameter, the volume or the surface density of voids has to be known. On the other hand, the Gurson model is based on the definition of porosity parameter. The porosity parameter can be directly recalculated to obtain the classical damage parameter in the sense of CDM. Both R-T and Gurson kinetics may be conveniently applied to describe the evolution of radiation induced damage in the form of clusters of voids embedded in the metallic matrix.

In order to illustrate the algorithm of lifetime estimation, a simple thin-walled cylindrical shell has been selected. The shell represents inner conductor of typical magnetic lens called horn and constitutes part of detector of particles. The horn is subjected to pulsed irradiation by the flux of secondary particles generated by solid target located coaxially and hit periodically by high energy particles beam. Also, it is subjected to cyclic mechanical loads related to heating/cooling operations (in the presence of boundary conditions) which leads to build-up of cyclic stress state containing localization. Combined radiation and mechanical loads lead to evolution of both damage components as a function of the number of cycles (time). It is worth pointing out, that the dpa distribution characteristic of the secondary particles flux emitted by a solid target has been parametrized and is presented in the form of product of power and exponential function. The lifetime estimation is based on the postulate that the damage function reaches its critical value at fracture.

References

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